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WABA DAM
DYNAMIC SOIL PROPERTIES

C.B.H. Cragg

The Waba Dam is founded on a deep deposit of marine clay. Dynamic properties of the upper 25 m of this deposit below the dam were measured about 9 years after construction. Seismic crosshole survey and resonant column test methods were used. Comparable shear modulus results were obtained by the two methods when laboratory resonant column samples were consolidated to confining pressures representative of pre-dam construction conditions. Modulus degradation and damping change with increasing strain are reported.

INTRODUCTION

An investigation of foundation soils at Waba Dam was cooperatively undertaken by Civil Research and the National Research Council of Canada to provide dynamic soil properties for the structure. Geotechnical Engineering initiated this study, with the support of Civil Works, and is performing the stability of analysis of the structure under earthquake loading, using the investigation data.

This report summarizes the parts of the investigation for which Civil Research was responsible.

SITE DESCRIPTION

Arnprior Generating Station is located in Arnprior, Ontario near the juncture of the Madawaska and Ottawa Rivers. Development of this hydroelectric project was completed about 1976. Waba Dam is a containment structure for the head pond of this development. Spanning an old gorge filled with up to 65 m of soft marine clay, Waba Dam has a height of about 8 m, a length of about 1100 m and wide stabilizing berms.

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740643-500-575	843.2	November 1, 1985	85-129-k

TEST PROGRAM

The field program included in situ measurements of shear modulus and taking samples for laboratory testing. Sampling and testing was done through the dam to a depth of 35 m.

In situ testing was done by the crosshole method using three linearly aligned boreholes. Details of this testing are described elsewhere/1/. Osterberg samples were taken during the in situ test program. These samples were 127 mm in diameter in the upper 20 m of testing and 76 mm in diameter in the lower 15 m of testing. Resonant column tests were performed on specimens trimmed from these samples. Marine clay specimens were consolidated to pressures representative of the area prior to construction of the dam. These pressures, ranging from 32 kPa to 150 kPa (Table I) were selected after consolidation tests performed by NRC had shown that the foundation soil had not consolidated commeasurate with the surcharge load of the dam/2/.

TEST RESULTS

Shear wave velocities (V_s) yielded by the seismic crosshole survey varied from 87 m/sec to 148 m/sec in the foundation marine clay (Table I). These values increased linearly with depth and compared closely with values measured in a natural marine clay deposit near Saunders GS/1/. Shear modulus (G) field values, calculated from V_s and in situ density (γ) using the formula

$$G = \frac{\gamma}{g} (V_s) \qquad (1)$$

yielded values ranging from 12 MPa to 35 MPa for the marine clay (Table I). Higher shear moduli - 56 MPa and 67 MPa - were measured in the compacted clay material of the dam.

The maximum shear moduli recorded in the laboratory resonant column tests ranged from 11.0 MPa to 38.3 MPa (Table I). Comparing the field and laboratory values of shear modulus showed the laboratory value was generally higher. Table I shows the resonant column $(G_{max})_{lab}$ value was 0.94 to 1.27 times the G_{field} value for foundation marine clay samples. Even though conservative consolidation pressures were used to prepare these samples, too high consolidation pressures may have caused the resonant column results to exceed field G values. Resonant column G is normally less than field G.

Modulus degradation with increasing strain was measured on 15 samples, three from the dam and twelve from the foundation soil. Log decrement measurements of damping were performed at the same time. Test results for the individual samples are presented in Appendix A. Figures 1 and 2 show envelopes of these test results. The marine clay foundation soil (Figure 1) showed a 30 to 40% shear modulus reduction at an average peak shear strain of 0.3%. As shown in Figure 1, the degradation of modulus ratio (G/Gmax) with increasing shear strain (α) is reasonably modelled by the formula

$$\frac{G}{G_{max}} = \frac{1}{1 + (\frac{\alpha}{0.3})} \qquad (2)$$

At low shear strain, the marine clay had damping values of 1 to 2%. Damping increased to maximum values between 4 and 8% at the maximum shear strains applied in the tests.

In comparison to the marine clay foundation, the compacted clay of the dam showed a more rapid decrease of modulus ratio with increasing shear strain. At an average peak shear strain of 0.1%, a 35 to 45% shear modulus reduction had occurred (Figure 2). Equation (2), that fit the foundation clay data reasonably well, does not provide a useful fit to compacted clay measurements. Damping of the compacted clay increased from a low value of 2% at low shear strains to a high of 5% at the maximum test shear strains (Figure 2).

SUMMARY

Resonant column test results for Waba Dam clays were reported and compared with field test results. Reasonable correlation was obtained between the two test methods. Shear modulus values for laboratory resonant column tests were 14% higher than the field values, possibly through use of a higher confining pressure than was acting effectively in the field. The marine clay foundation soil showed a 30% to 40% decrease in shear modulus at maximum test shear strains while the dam core clay modulus decreased 35% to 45%. A mathematical model was presented which reasonably predicted the modulus degradation of the marine clay but not the clay core. Maximum damping values for the marine clay were 4% to 8% and for the clay core were about 5%.

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REFERENCES

1. Cragg, C.B.H. "Waba Dam - Seismic Crosshole Survey". Research Division Report No 84-349-K, November, 1984.

2. Personal communication with Dr. K.T. Law, NRC.

TABLE I

SHEAR MODULUS SUMMARY FOR WABA DAM

Test Depth (m)	Confining Pressure (kPa)	Initial Density (kg/m^3)	V_s (m/sec)	$(G)_{field}$ (MPa)	$(G_{max})_{lab}$ (MPa)	$\frac{G\ lab}{G\ field}$	
6.4	80	2002	183	66.8	44.3	0.66	Waba Clay Core
9.9	104	1879	177	55.9	44.6	0.80	
14.6	32	1547	87	11.7	11.0	0.94	Marine Clay Foundation Soil
15.2	36	1547	87	11.7	13.0	1.11	
15.9	39	1564	90	12.6	12.9	1.02	
16.8	45	1532	92	12.9	16.4	1.27	
18.6	55	1606	96	14.8	17.3	1.17	
19.5	61	1527	99	14.9	18.2	1.22	
20.1	64	15.5	105	17.3	21.3	1.23	
23.2	87	1581	112	19.8	24.2	1.22	
26.2	100	1600	125	25.0	28.1	1.12	
29.3	118	1571	134	28.1	30.4	1.08	
32.3	136	1606	136	29.6	34.4	1.16	
34.8	150	1596	148	34.9	38.3	1.10	

V_s - shear wave velocity

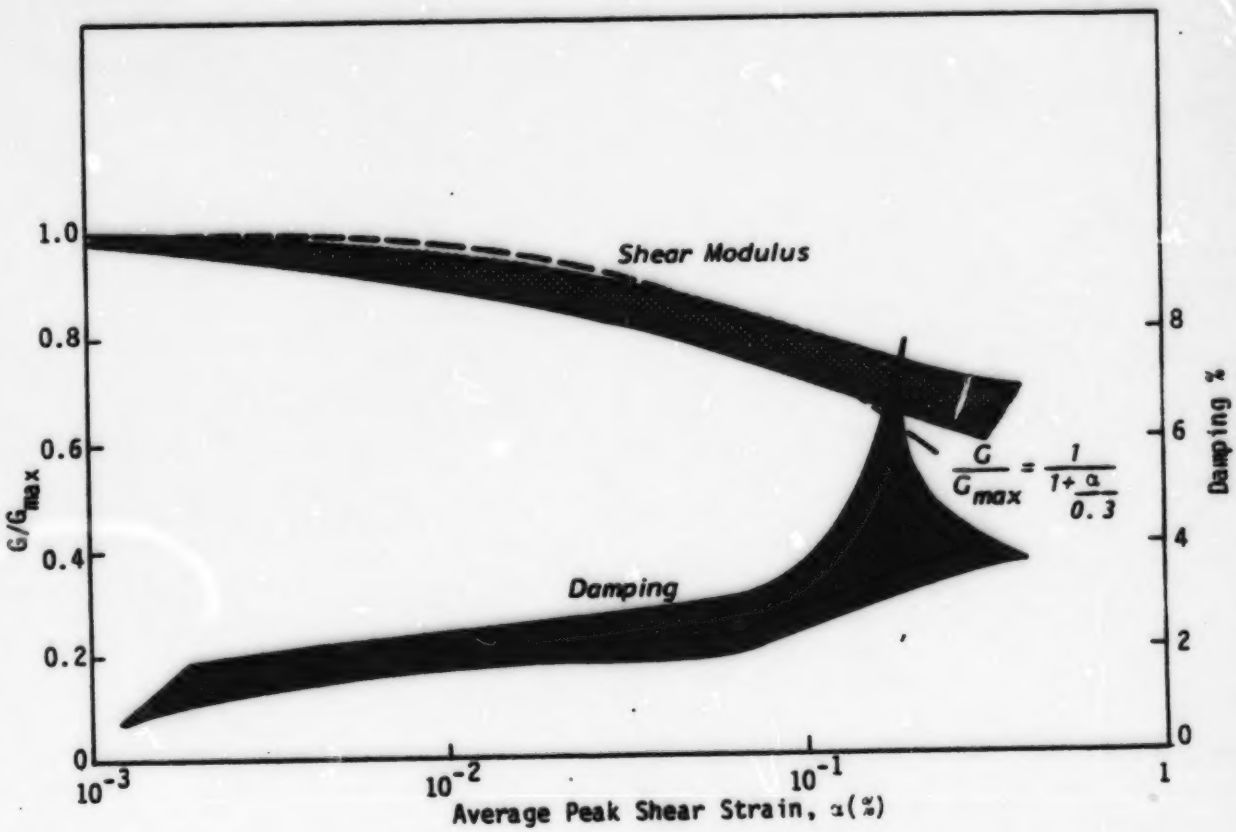


FIGURE 1

SUMMARY OF RESONANT COLUMN TESTS
ON WABA DAM FOUNDATION SOIL
(12 TESTS)

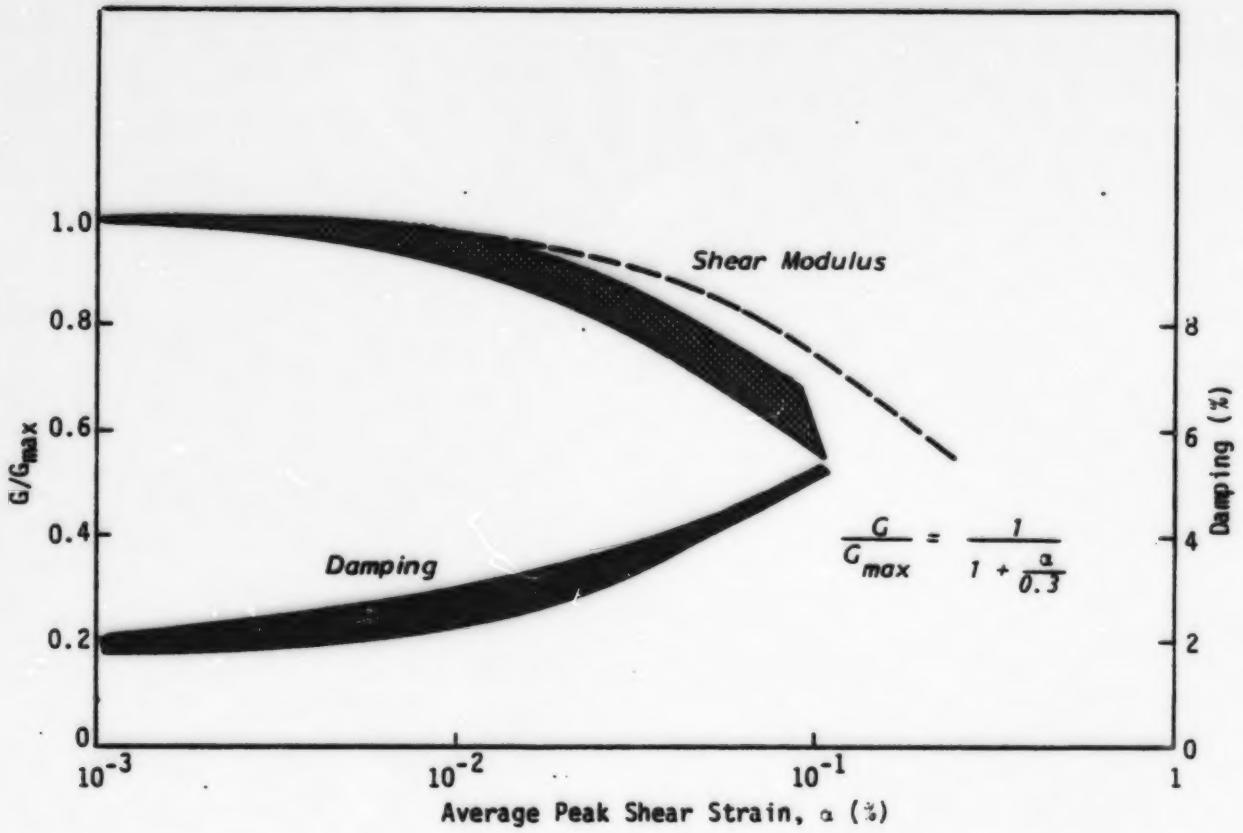


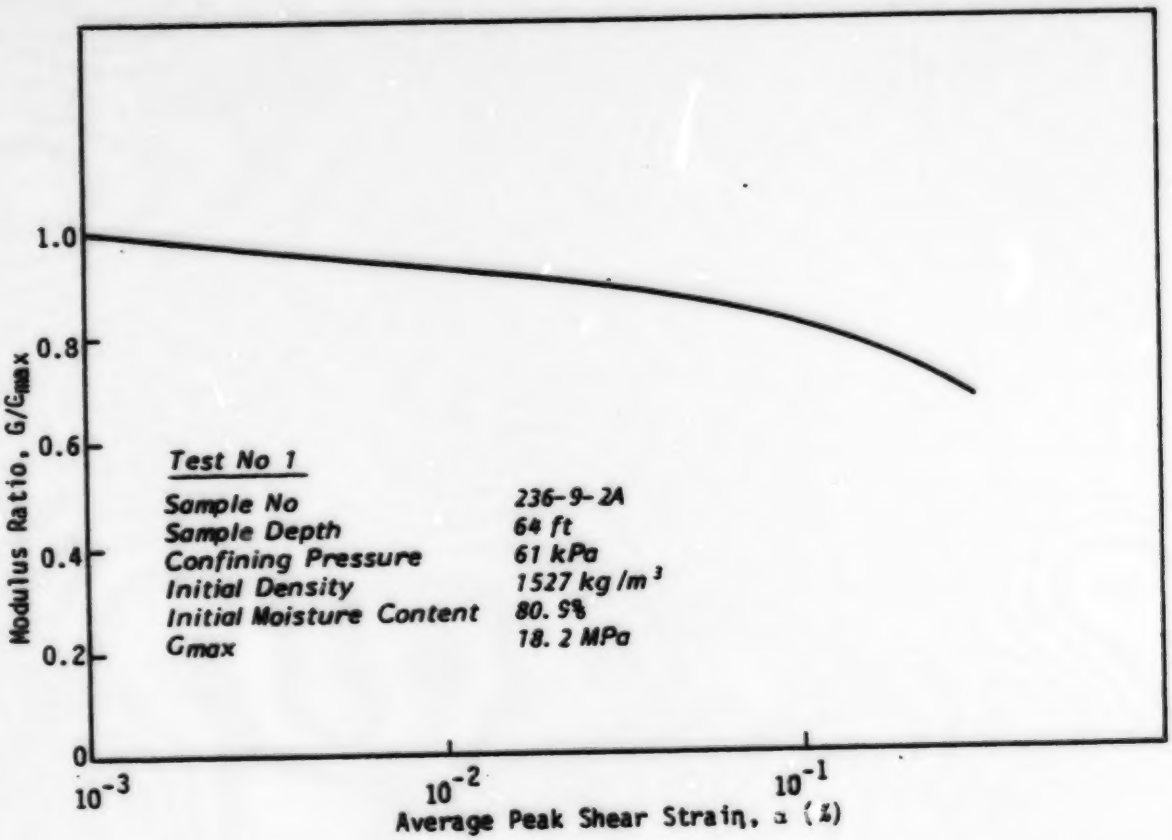
FIGURE 2

SUMMARY OF RESONANT COLUMN TESTS ON WABA DAM CORE CLAY (3 TESTS)

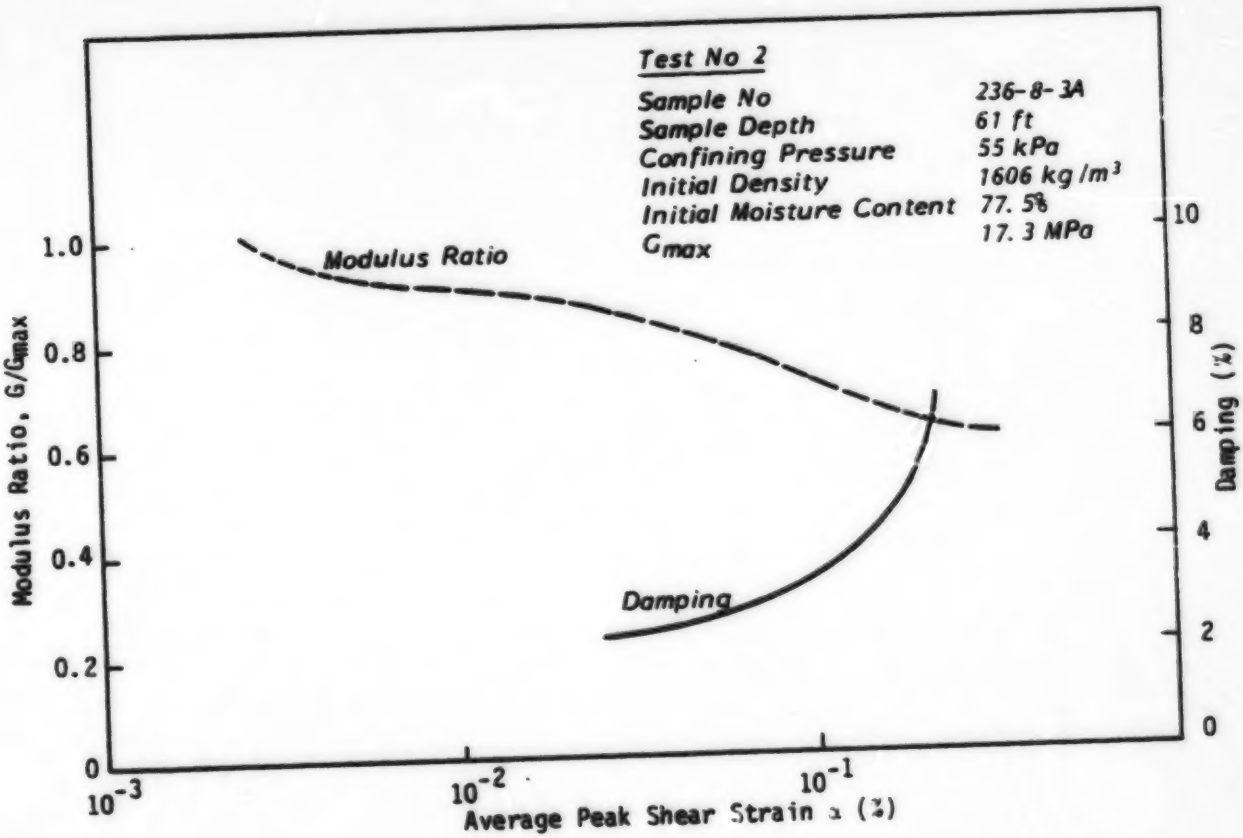
168884-RD

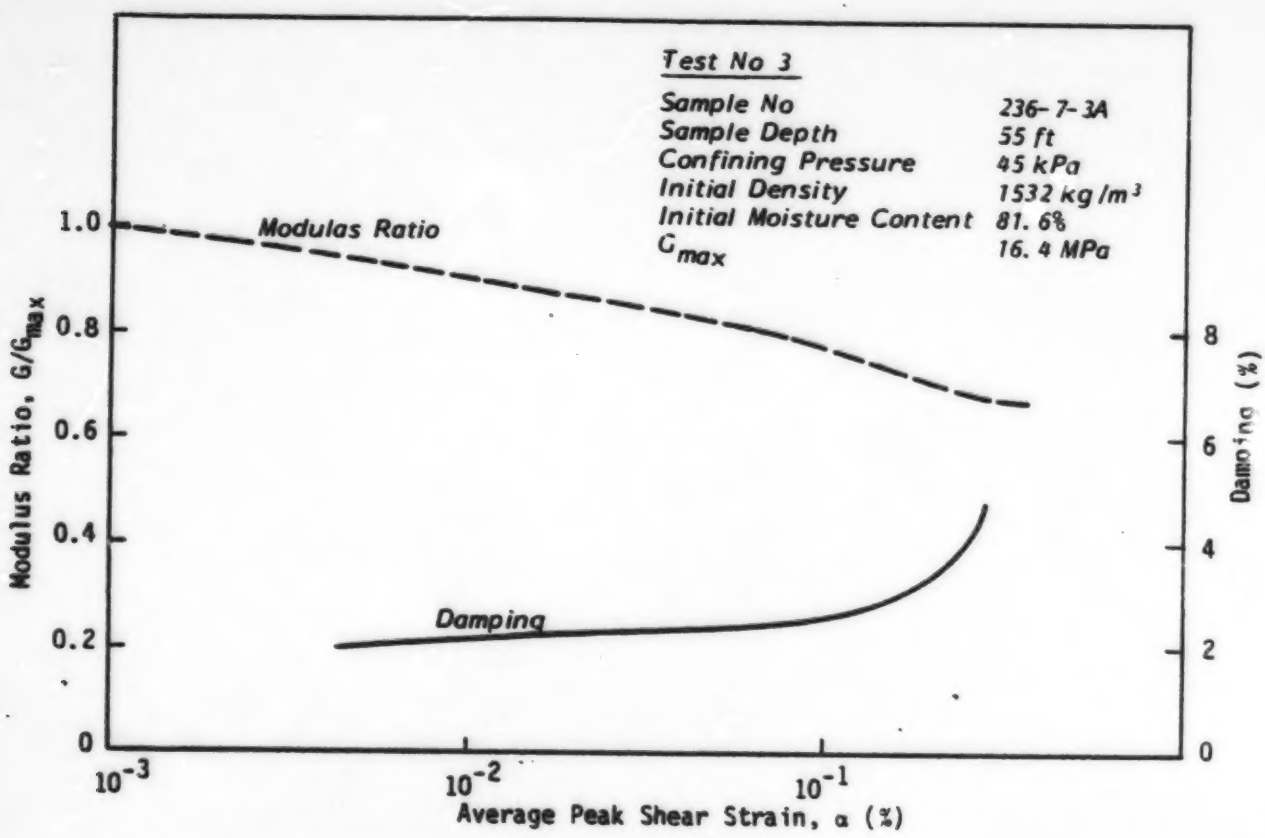
APPENDIX A

INDIVIDUAL RESONANT COLUMN TEST RESULTS

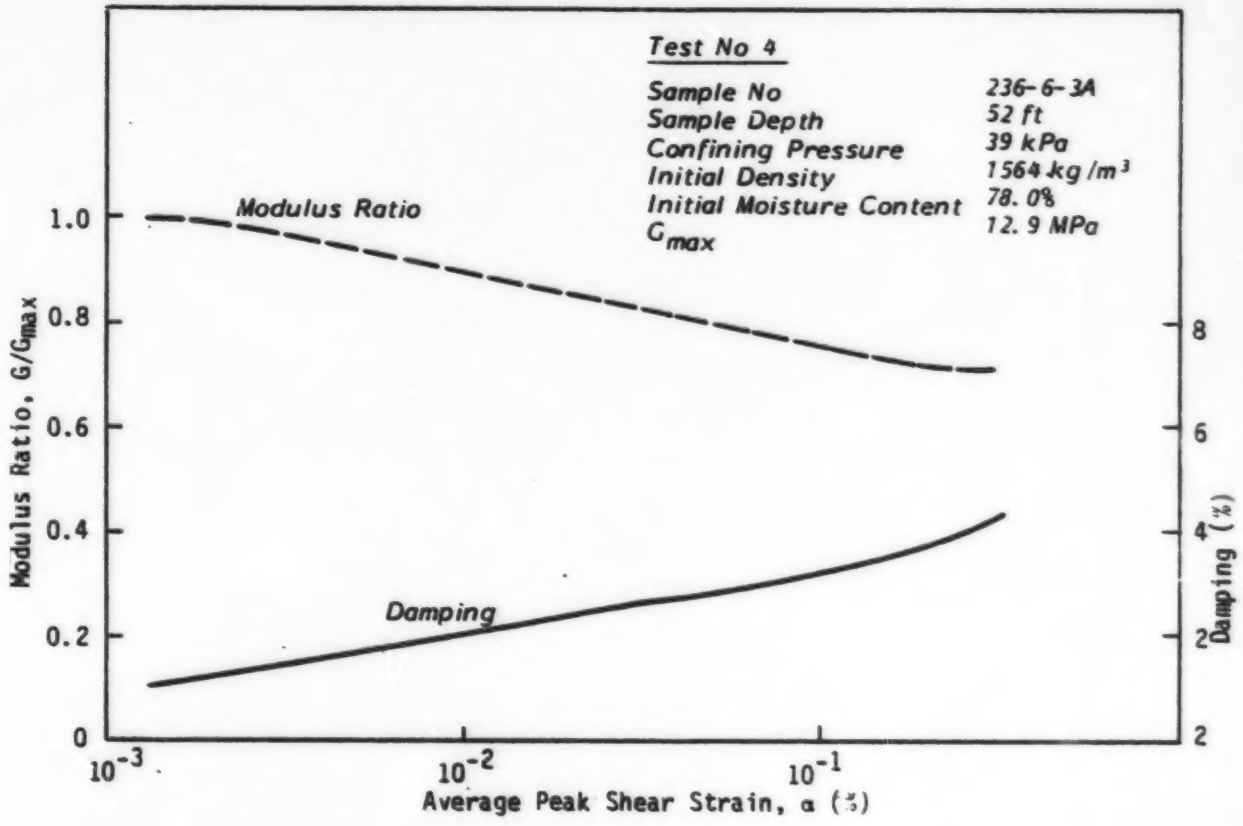

1.0
0.8
0.6
0.4
0.2
0
Modulus Ratio, G/Gmax
Test No 1
Sample No 236-9-2A
Sample Depth 64 ft
Confining Pressure 61 kPa
Initial Density 1527 kg/m3
Initial Moisture Content 80.9%
Gmax 18.2 MPa
10-3
10-2
10-1
Average Peak Shear Strain, γ (%)

168885-RD

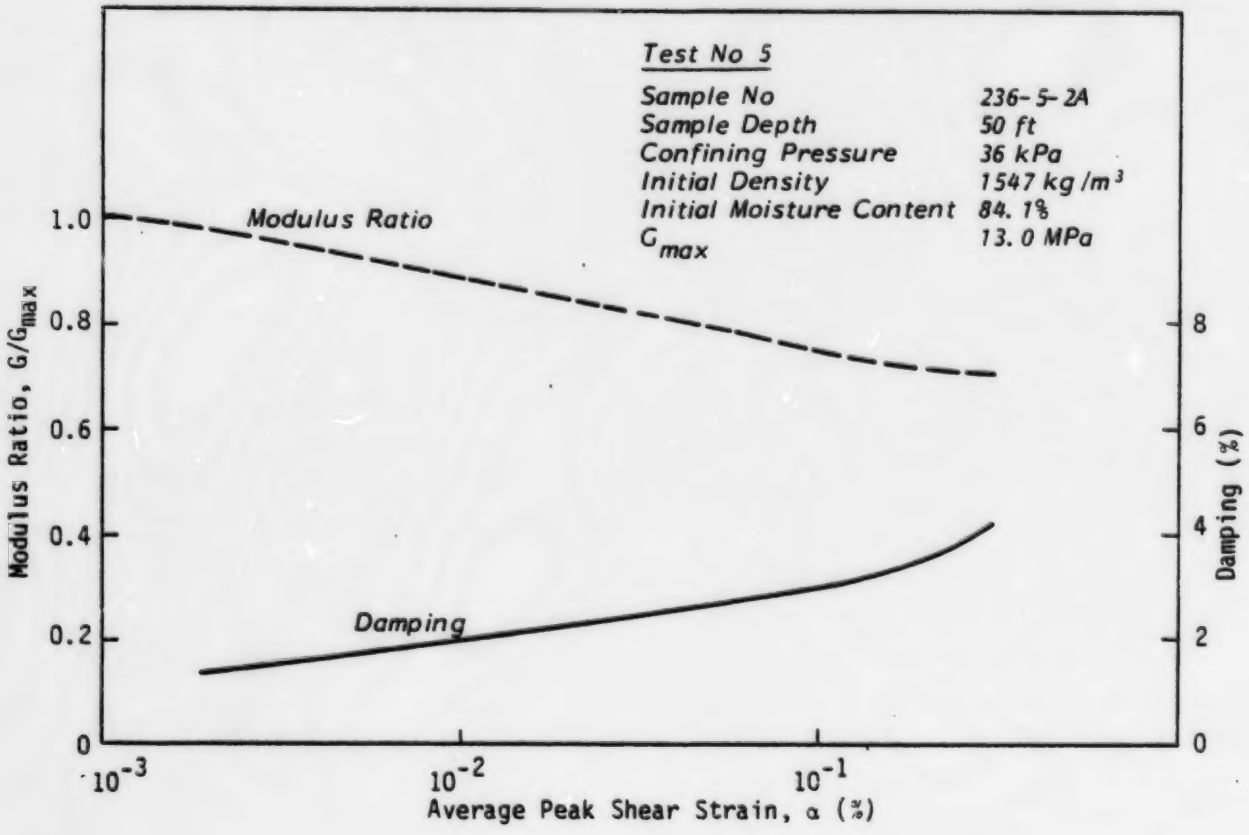

Test No 2
Sample No 236-8-3A
Sample Depth 61 ft
Confining Pressure 55 kPa
Initial Density 1606 kg/m³
Initial Moisture Content 77.5%
Gmax 17.3 MPa
Modulus Ratio
Damping
Modulus Ratio, G/Gmax
Damping (%)
Average Peak Shear Strain γ (%)
1.0
0.8
0.6
0.4
0.2
0
10
8
6
4
2
0
10⁻³
10⁻²
10⁻¹


Test No 3
Sample No 236-7-3A
Sample Depth 55 ft
Confining Pressure 45 kPa
Initial Density 1532 kg/m³
Initial Moisture Content 81.6%
Gmax 16.4 MPa
Modulas Ratio
Damping
Modulus Ratio, G/Gmax
Damping (%)
1.0
0.8
0.6
0.4
0.2
0
8
6
4
2
0
10⁻³
10⁻²
10⁻¹
Average Peak Shear Strain, α (%)

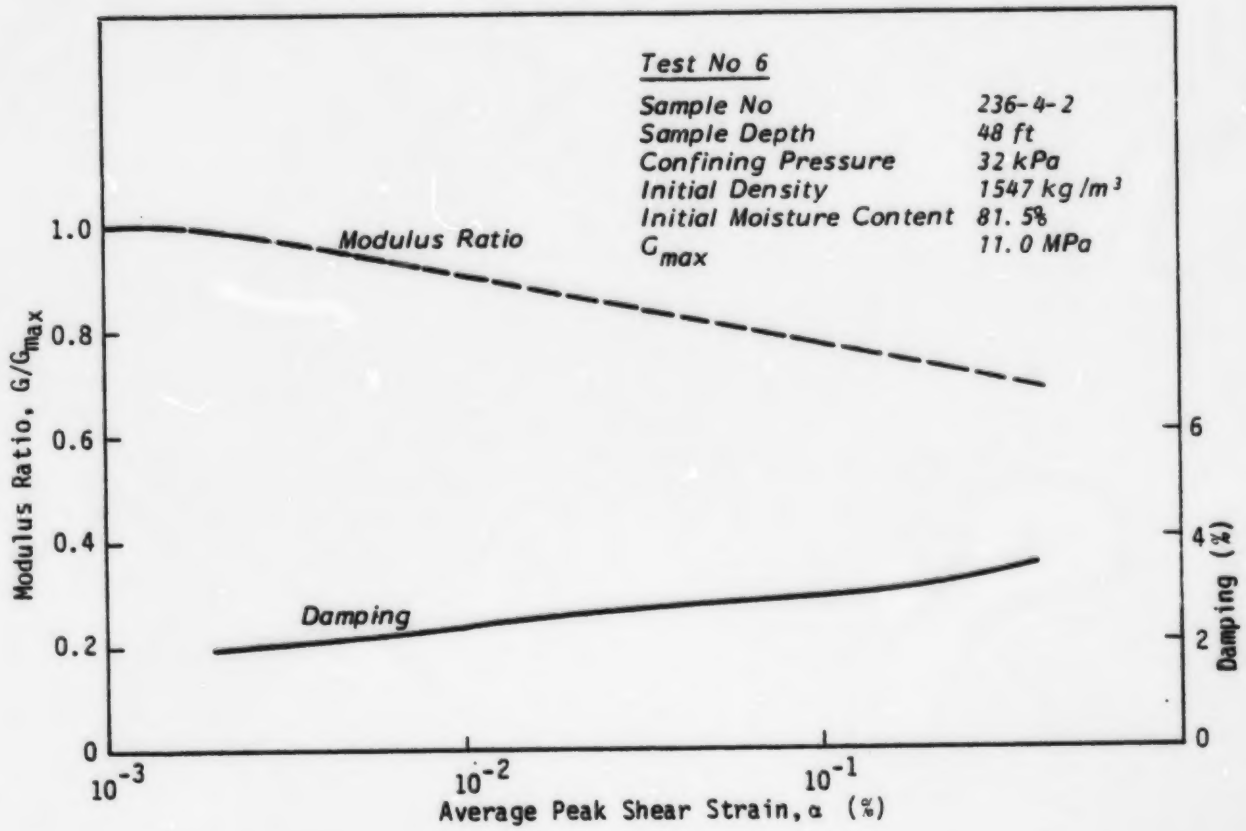
168887-RD


Test No 4
Sample No 236-6-3A
Sample Depth 52 ft
Confining Pressure 39 kPa
Initial Density 1564 kg/m³
Initial Moisture Content 78.0%
Gmax 12.9 MPa
Modulus Ratio
Damping
Modulus Ratio, G/Gmax
Damping (%)
1.0
0.8
0.6
0.4
0.2
0
8
6
4
2
10⁻³
10⁻²
10⁻¹
Average Peak Shear Strain, α (%)

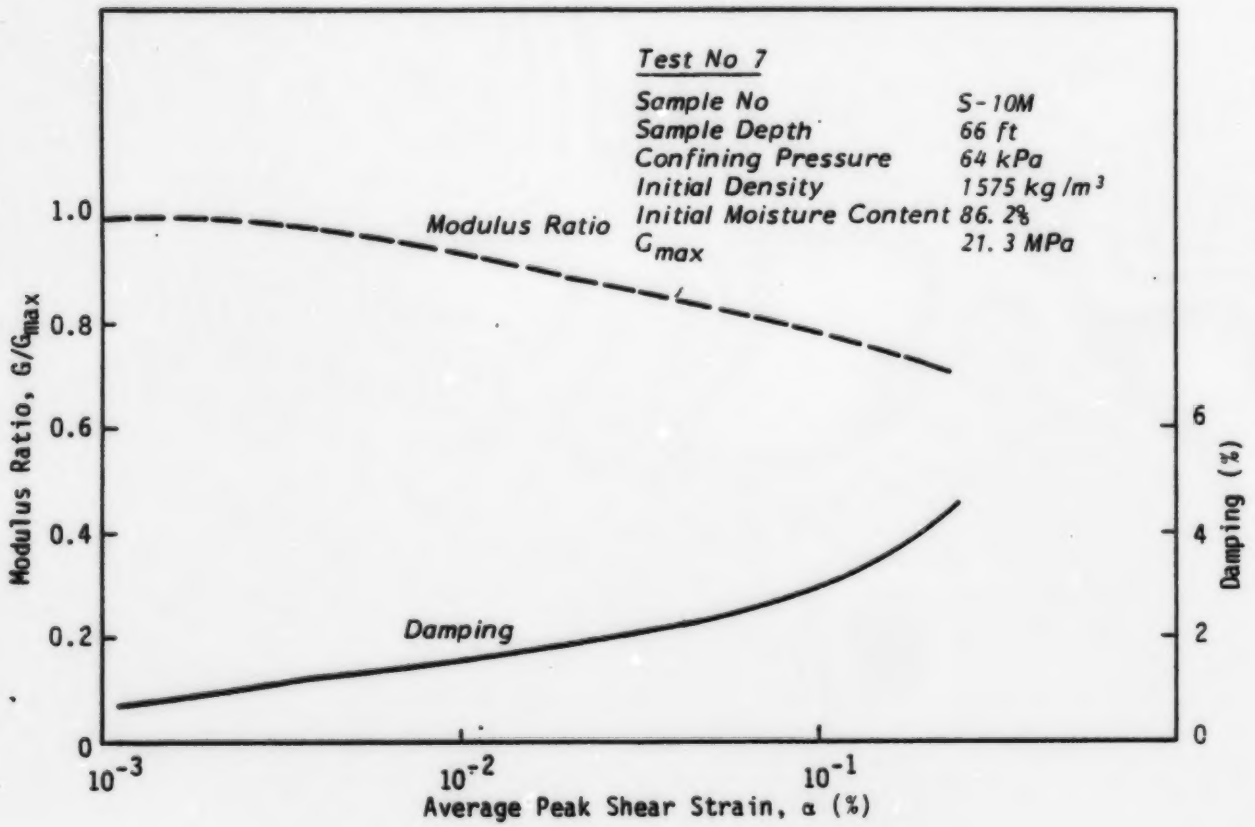
168888-RD


Test No 5
Sample No 236-5-2A
Sample Depth 50 ft
Confining Pressure 36 kPa
Initial Density 1547 kg/m³
Initial Moisture Content 84.1%
G max 13.0 MPa
Modulus Ratio
Damping
Modulus Ratio, G/G max
Damping (%)
1.0
0.8
0.6
0.4
0.2
0
8
6
4
2
0
10⁻³
10⁻²
10⁻¹
Average Peak Shear Strain, α (%)

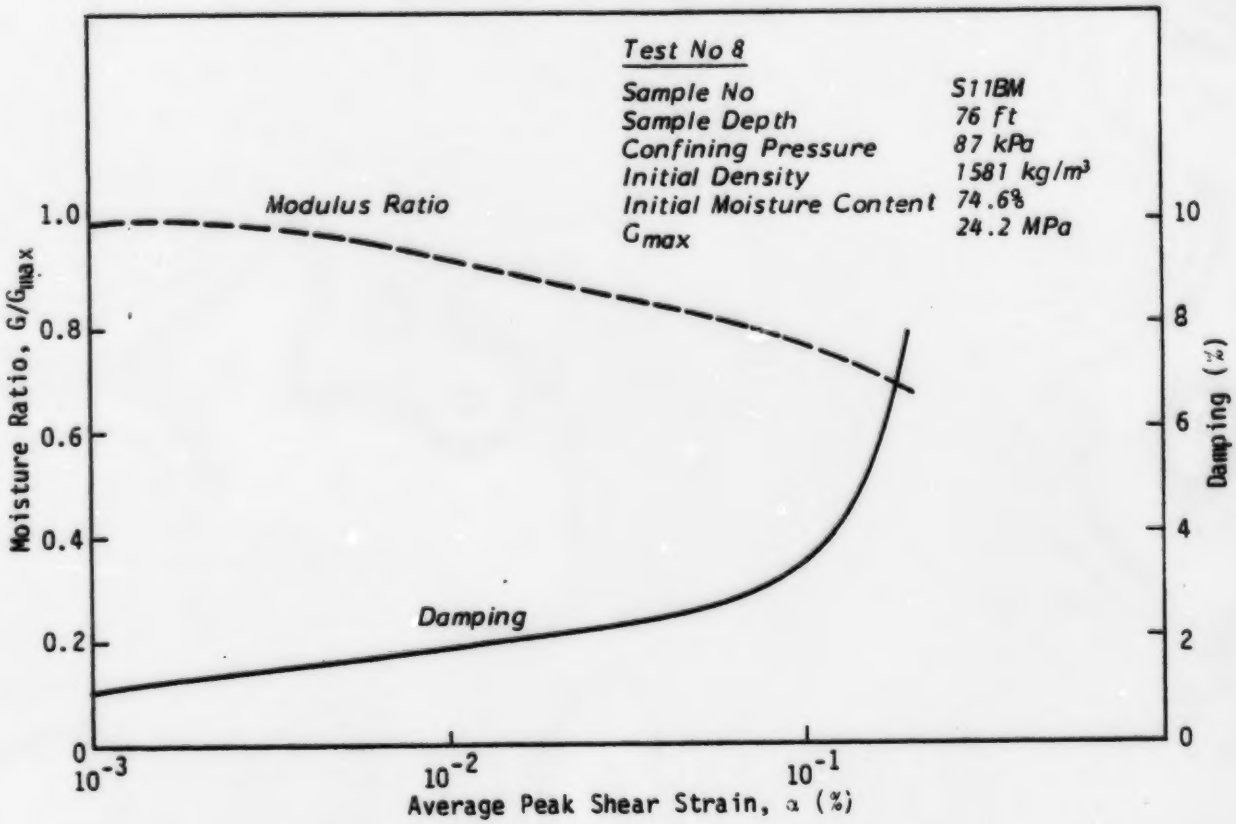
168889-RD

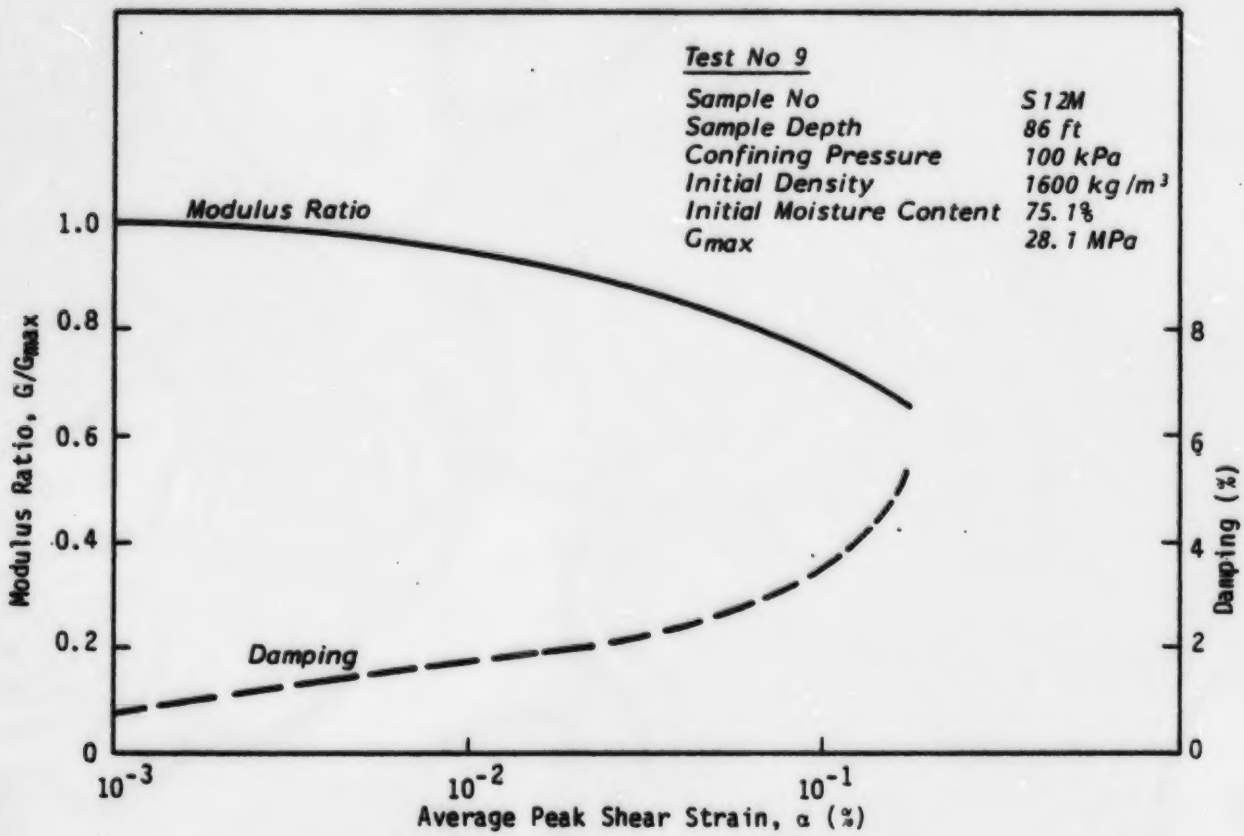

Test No 6
Sample No 236-4-2
Sample Depth 48 ft
Confining Pressure 32 kPa
Initial Density 1547 kg/m³
Initial Moisture Content 81.5%
G max 11.0 MPa
Modulus Ratio
Damping
Modulus Ratio, G/G max
Damping (%)
1.0
0.8
0.6
0.4
0.2
0
6
4
2
0
10⁻³
10⁻²
10⁻¹
Average Peak Shear Strain, α (%)

168890-RD

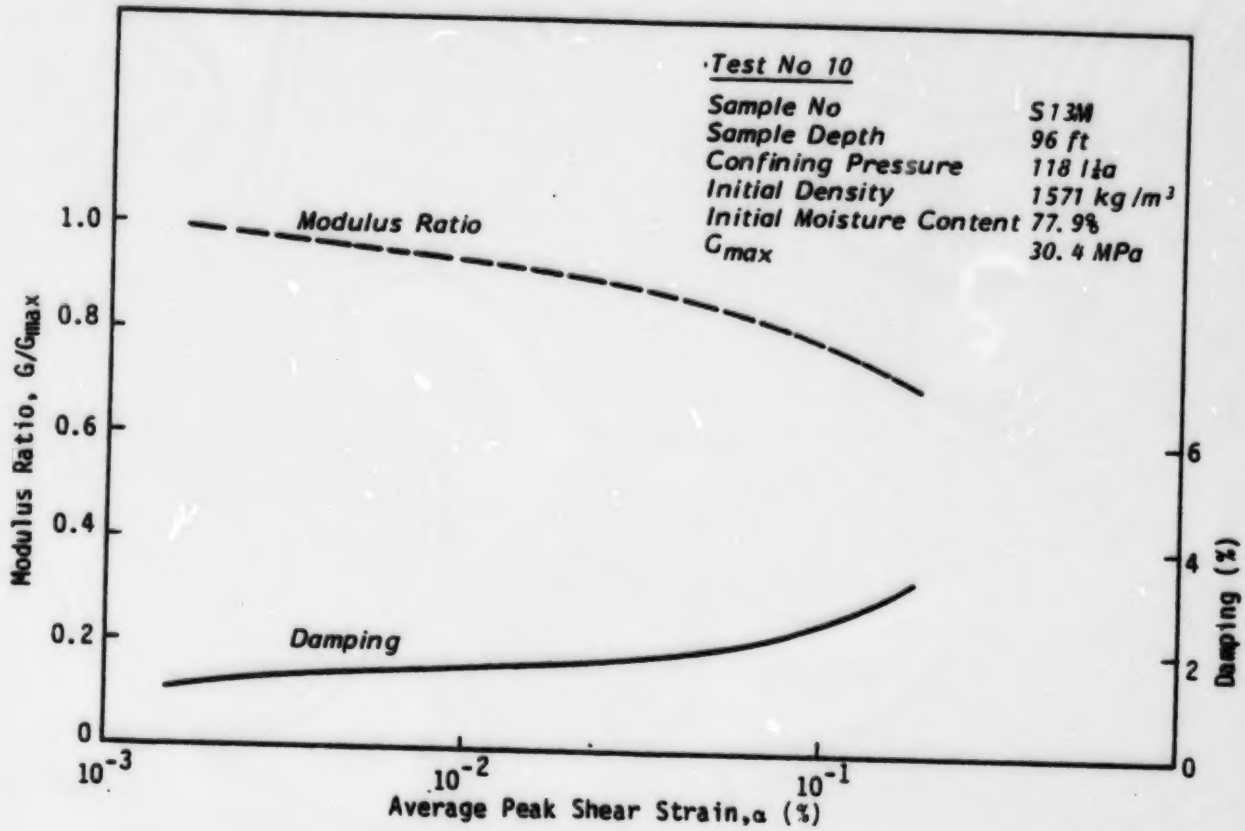

Test No 7
Sample No S-10M
Sample Depth 66 ft
Confining Pressure 64 kPa
Initial Density 1575 kg/m³
Initial Moisture Content 86.2%
G_{max} 21.3 MPa
Modulus Ratio
Damping
Modulus Ratio, G/G_{max}
Damping (%)
Average Peak Shear Strain, α (%)
1.0
0.8
0.6
0.4
0.2
0
6
4
2
0
10^{-3}
10^{-2}
10^{-1}

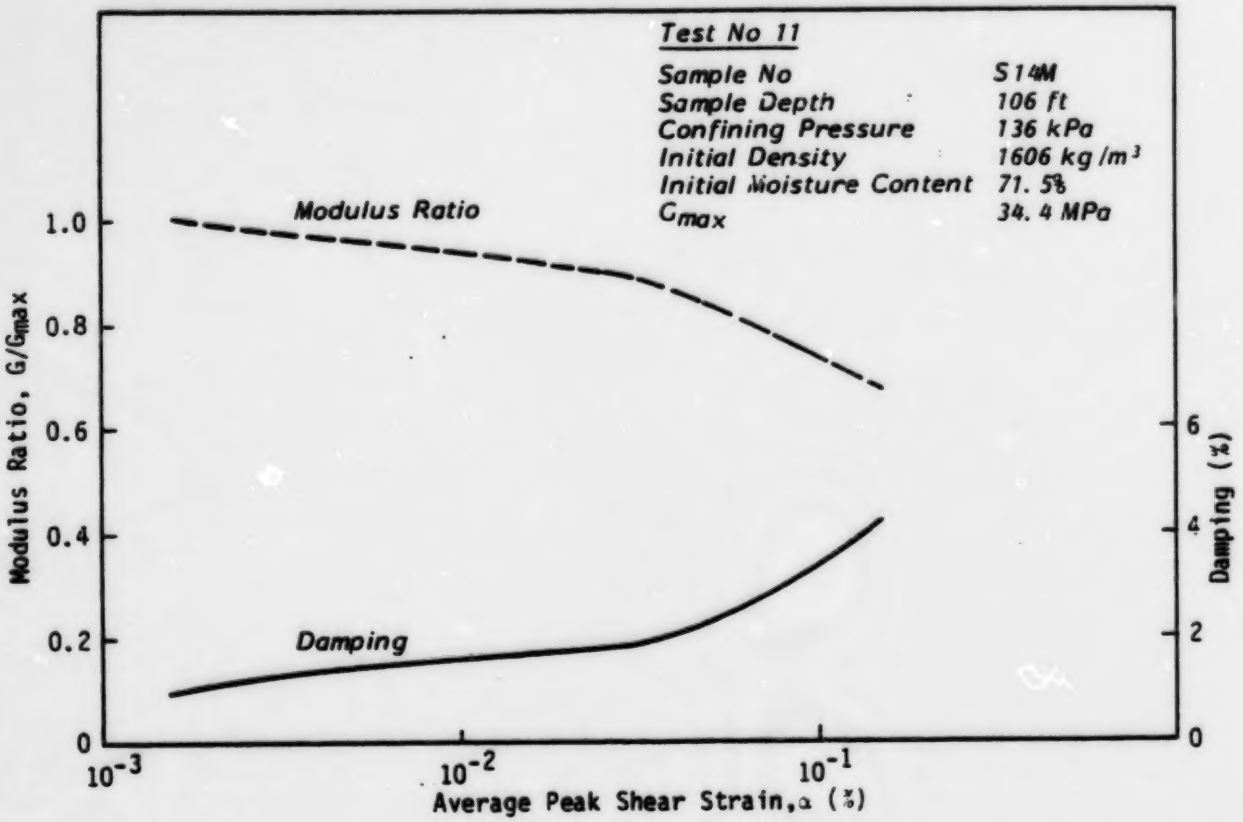
168891-RD


Test No 8
Sample No S11BM
Sample Depth 76 ft
Confining Pressure 87 kPa
Initial Density 1581 kg/m³
Initial Moisture Content 74.6%
Gmax 24.2 MPa
Modulus Ratio
Damping
Moisture Ratio, G/Gmax
Damping (%)
Average Peak Shear Strain, α (%)
1.0
0.8
0.6
0.4
0.2
0
10
8
6
4
2
0
10⁻³
10⁻²
10⁻¹

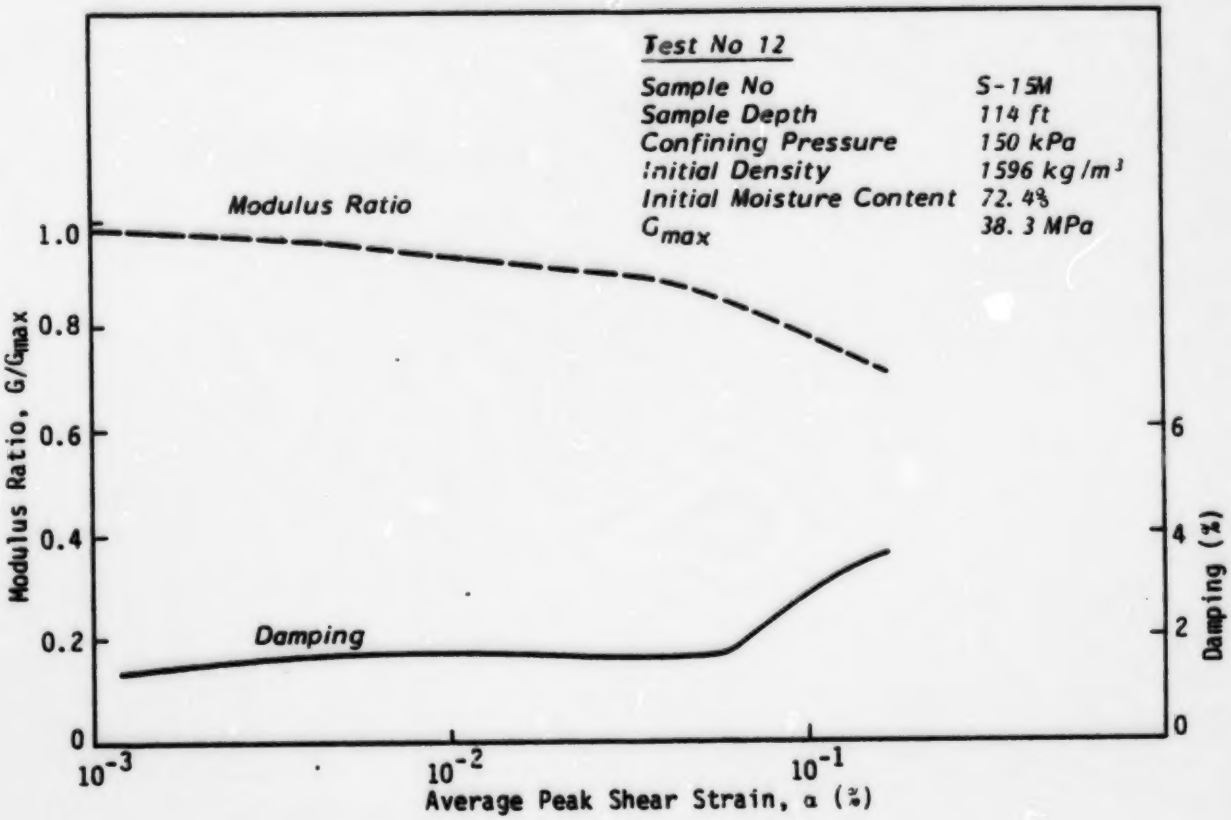

Test No 9
Sample No S12M
Sample Depth 86 ft
Confining Pressure 100 kPa
Initial Density 1600 kg/m³
Initial Moisture Content 75.1%
Gmax 28.1 MPa
Modulus Ratio
Damping
Modulus Ratio, G/Gmax
Damping (%)
1.0
0.8
0.6
0.4
0.2
0
8
6
4
2
0
10⁻³
10⁻²
10⁻¹
Average Peak Shear Strain, α (%)

168893-RD

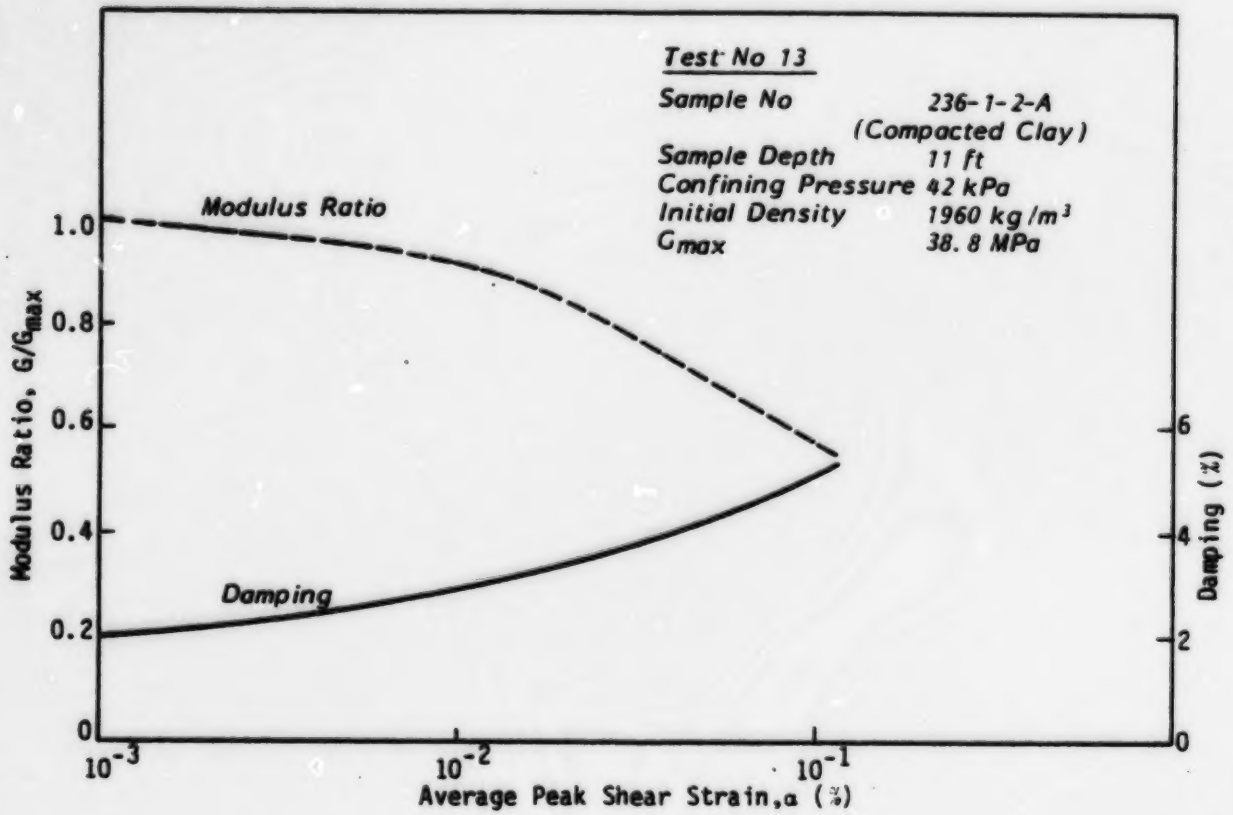

Test No 10
Sample No S13M
Sample Depth 96 ft
Confining Pressure 118 kPa
Initial Density 1571 kg/m³
Initial Moisture Content 77.9%
Gmax 30.4 MPa
Modulus Ratio
Damping
Modulus Ratio, G/Gmax
Damping (%)
Average Peak Shear Strain, α (%)
1.0
0.8
0.6
0.4
0.2
0
6
4
2
0
10⁻³
10⁻²
10⁻¹


Test No 11
Sample No S14M
Sample Depth 106 ft
Confining Pressure 136 kPa
Initial Density 1606 kg/m³
Initial Moisture Content 71.5%
Gmax 34.4 MPa
Modulus Ratio
Damping
Modulus Ratio, G/Gmax
Damping (%)
Average Peak Shear Strain, γ (%)
1.0
0.8
0.6
0.4
0.2
0
6
4
2
0
10⁻³
10⁻²
10⁻¹

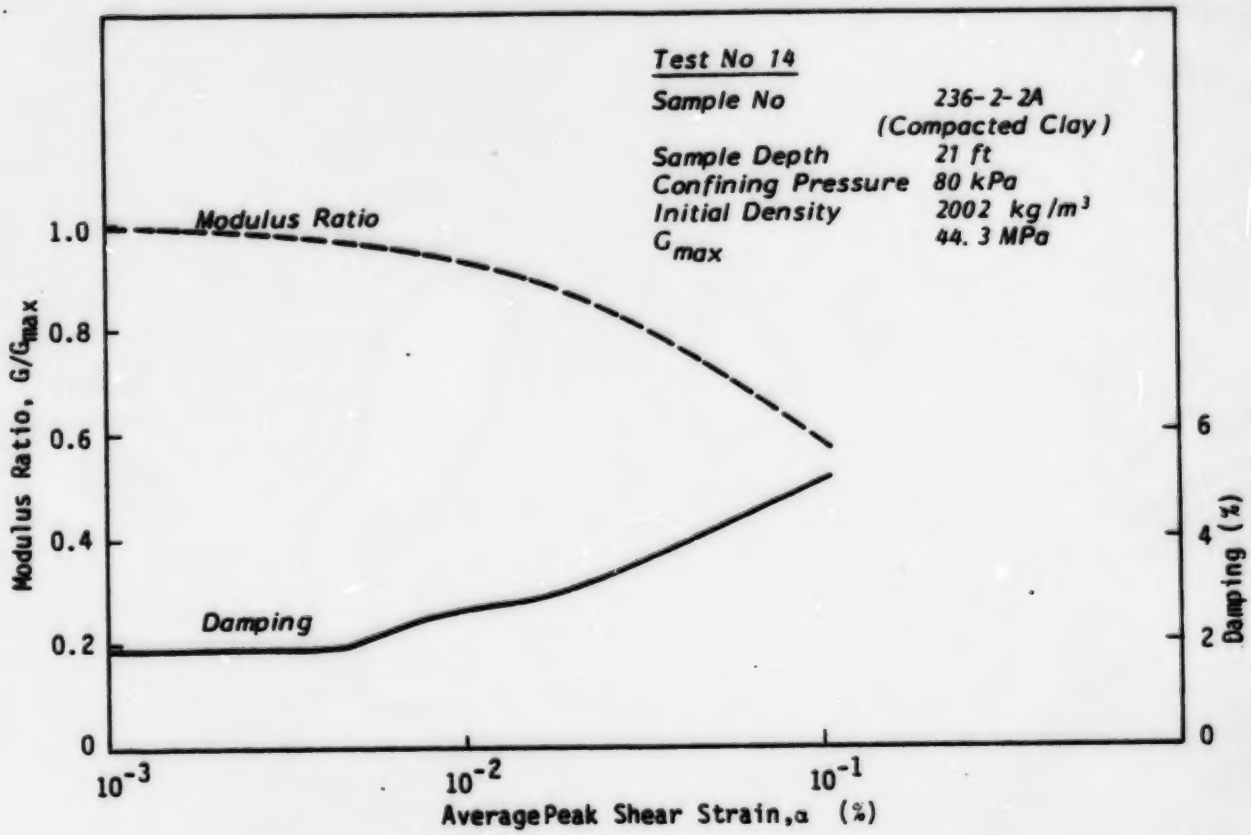
168895-RD


Test No 12
Sample No S-15M
Sample Depth 114 ft
Confining Pressure 150 kPa
Initial Density 1596 kg/m³
Initial Moisture Content 72.4%
G_{max} 38.3 MPa
Modulus Ratio
Damping
Modulus Ratio, G/Gmax
Damping (%)
1.0
0.8
0.6
0.4
0.2
0
6
4
2
0
10^{-3}
10^{-2}
10^{-1}
Average Peak Shear Strain, α (%)

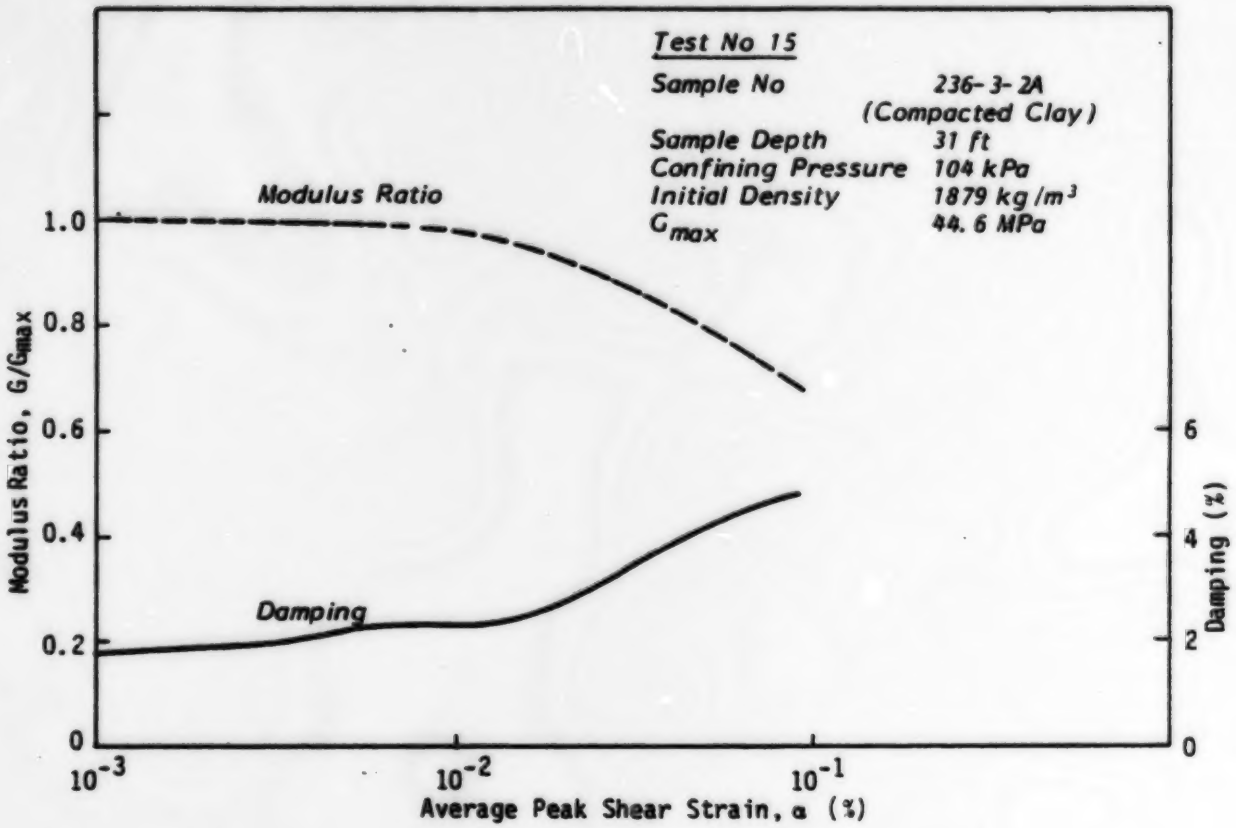
168896-RD


Test No 13
Sample No 236-1-2-A
(Compacted Clay)
Sample Depth 11 ft
Confining Pressure 42 kPa
Initial Density 1960 kg/m³
Gmax 38.8 MPa
Modulus Ratio
Damping
Modulus Ratio, G/Gmax
Damping (%)
1.0
0.8
0.6
0.4
0.2
0
6
4
2
0
10⁻³
10⁻²
10⁻¹
Average Peak Shear Strain, α (%)

168897-RD


Test No 14
Sample No 236-2-2A (Compacted Clay)
Sample Depth 21 ft
Confining Pressure 80 kPa
Initial Density 2002 kg/m³
Gmax 44.3 MPa
Modulus Ratio
Damping
Modulus Ratio, G/Gmax
Damping (%)
1.0
0.8
0.6
0.4
0.2
0
6
4
2
0
10⁻³
10⁻²
10⁻¹
Average Peak Shear Strain, α (%)

168898-RD


Test No 15
Sample No 236-3-2A
(Compacted Clay)
Sample Depth 31 ft
Confining Pressure 104 kPa
Initial Density 1879 kg/m³
Gmax 44.6 MPa
Modulus Ratio
Damping
Modulus Ratio, G/Gmax
Damping (%)
1.0
0.8
0.6
0.4
0.2
0
6
4
2
0
10⁻³
10⁻²
10⁻¹
Average Peak Shear Strain, α (%)

168899-RD